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Research paper

Exergy analysis of a four pan jaggery making process

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ABSTRACT

Jaggery is a non-traditional sweetener that is produced from boiling sugarcane juice. Due to the energy intensive nature of the combustion process in jaggery making, previous studies in literature have presented various process and equipment modifications to affect its energy efficiency. This study adds to the understanding of the resource transformations and consumptions in the jaggery process by presenting its exergy analysis. The baseline process was operationally modified for which the exergy efficiency and exergy destruction are calculated. Through the modifications, the exergy efficiency and exergy destruction increased by 11.2% and 0.8% respectively. A significant amount of exergy was wasted as surplus heat in the form of flue gas, which reduced by 11.5% due to process modifications. The results show that while the most evident form of resource waste was due to flue gas released into the environment, the largest form of resource consumption was actually due to exergy destruction arising from irreversibilities in combustion, a result not clearly evident through energy analysis alone. Through modelling process flows in terms of exergy, the analysis presented in this paper increases the visibility of the resource consumptions and losses in the jaggery making process. This study should aid the efforts of researchers and practitioners aiming to reduce resource consumption in the jaggery making process.

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1. Introduction

Jaggery is natural unrefined sugar which is consumed in Asia, Africa, Latin America and the Caribbean (Singh, 2013). Its production is a significant part of the agricultural industry in the Indian subcontinent, mostly prevalent in its rural population which is 65% of the total (The world bank, 2015). In India, about 30% of the sugarcane produced goes into making jaggery and unrefined sugar (Gonsalves, 2006). Rao et al. (2007) reported similar statistics that the jaggery industry used 24.5% of the cane produced in India for the year 2007. A typical jaggery making processes uses open pan furnaces to concentrate the cane juice to required specifications. This is an energy intensive process which has attracted researchers to understand the energy and mass transformations in the process, and to investigate strategies to minimize its energy use. For example, Anwar (2010) made equipment modifications to improve the energy efficiency of the process, by applying the concept of fins to the open pan jaggery making furnace, which resulted in significant energy savings (31.34%). In another example of equipment modification, Manjare and Hole (2016) employed

preheating using the flue gas to improve the thermal performance of the process. Jakkamputi and Mandapati (2016) showed that a specific bagasse consumption per kilogramme of jiggery could be reduced by 0.23 kg if solar collectors were employed to preheat the cane juice. Shiralkar et al. (2014) demonstrated efficiency improvements by improving combustion; and analysed both single, and multi pan furnaces. Dampers at air inlets were used to reduce excess air for combustion, thus increasing energy efficiency. In another study along similar lines of investigation, Sardeshpande et al. (2010) modified the fuel feeding rate to achieve a higher energy efficiency. Tiwari et al. (2004) conducted an experimental study to determine the convection rate of heat transfer for boiling cane juice. La Madrid et al. (2016) performed a study which demonstrated the use of computational fluid dynamics (CFD) towards designing highly energy efficient jiggery making equipment. A follow up study by La Madrid et al. (2017) found through the use of CFD analysis that a fire-tube pan heat exchanger would result in better thermal performance as compared to the conventional flat-pan design.

It is important to note that all the studies that have been mentioned are based on energy analysis. The limitation of such an approach is that it does not allow the analyst to consider the quality of energy along with an inability to identify the locations of irreversibilities along the process. This paper, by presenting an exergy analysis, aims to provide a greater visibility of the losses

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associated with resource transformations that occur during the jaggery making process, which is its main contribution. Additionally, the study will add to the scarce body of literature aimed at improving the resource efficiency of the jaggery process.

This paper is based on the experimental study previously conducted by Sardeshpande et al. (2010) in which the energy efficiency in a four-pan furnace arrangement was analysed and improved through process operational modifications. Essentially, the fuel feed rate was modified to improve the energy performance of the four-pan furnace system. This paper presents an exergy analysis of the same process with the aim of providing a deeper understanding of resource transformations and consumptions that occurs during the process. All flows for the baseline and modified scenario are modelled in terms of exergy followed by the calculation of exergy efficiency and exergy destruction in the process. Exergy is a property of not only the system, but also the surroundings, and therefore the selection of reference environment (R.E.), directly impacts the results generated by exergy analysis. Each reference environment model is fixed by its chemical composition, and the exergy values derived from them are necessarily linked it. For this study, the widely accepted and used reference environment, proposed by Szargut et al. (2005) is used. Unless otherwise stated, the chemical exergy values of the elements and compounds in the analysis, derived from the selected R.E., are taken from CIRCE (2008).

Before describing the exergy analysis, it is important to highlight some benefits of adopting the exergy approach which were the motivation for this study. Exergy has been defined by Szargut et al. (1988) as “the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes”. A major benefit of using the exergy approach is the fact that it allows one to account for the qualitative nature of mass as well as energy flows. Therefore, a more accurate representation of surplus or waste resource flows can be obtained as compared to energy analysis alone. Additionally, the analysis of resource consumption is not segregated into mass and energy categories, rather both are represented in common physical units. This is helpful when an objective comparison between various improvement to a manufacturing is required that effect its energy, material and water efficiency. Also, when resource transformations occur, both their mass and energy are conserved even though their useful potential is lost, therefore making it difficult to account for resource consumption in an energy analysis. On the other hand, resource transformations are accompanied by the consumptions of exergy that are related to irreversibilities in real processes, termed as exergy destruction. This makes exergy particularly useful when the goal is to account for natural resource consumption in a system. For these reasons, exergy analysis has been considered a suitable technique for resource accounting in environmental science (Gong and Wall, 2001; Seager et al., 2002). Prominent researchers such Szargut et al. (2002) and Rosen et al. (2008) have linked the depletion of non-renewable natural resources to the consumption of non-renewable stocks of exergy, precisely due to the above mentioned reasons. In this paper also, the consumption of non-renewable resources is indicated by the consumption of non-renewable exergy. Section 2 provides a brief introduction to the jaggery making process while also detailing the analysis method, the exergy balance and the methodology for calculating the exergy content for all flows in the process. Section 3 presents the results of the exergy analysis along with a detailed discussion. The possibility of exergy reuse through integration with a fictitious secondary process is also provided that adds to the understanding of resource consumptions in the jaggery making process. Finally, the summary and concluding comments are provided in Section 4.

2. Jaggery production case study

The case study presented here is based on a processing plant in India. The jaggery production process involves extracting juice from the sugar-cane using a crushing machine. The juice is then transported via a conveyor to a set of pans. The juice in the pans is continuously stirred while being heated by a furnace up to a required temperature. The juice is thickened as water is driven off until it reaches the required specification when it is cooled and finally solidified in moulds. Fig. 1 depicts this process.

The instrumentation used for the experimentation in the previous study by Sardeshpande et al. (2010) is provided in Table 1. Based on experimental measurements of the base case, the energy efficiency of the process was improved by ensuring complete combustion. This was accomplished by shifting to a controlled and lowered bagasse feed rate that also increased the batch processing time. These changes resulted in a saving of 28% of the bagasse supplied to the baseline operation. This also had an associated effect of lowering the operating temperature of the furnace thus reducing the flue gas temperature from 900 °C to 700 °C. It should be noted that this was the minimum possible operating temperature at which the product quality was satisfactory. While the mass and energy balances were established in the previous study, this paper implements an exergy balance for the jaggery process which is presented in the following Section 2.1.

2.1. System analysis

In order to establish the mass, energy and exergy balances, a control volume approach has been taken. The evaporation of water from the juice is the core of the process, and this is accomplished in a bagasse fired furnace. The skin of the sugar-cane left after crushing is called bagasse and serves as renewable fuel. Before the bagasse can be used, it needs to be dried. Depending upon the recipe, small amounts of chemical additives (such as lime and okra juice) are also added to the cane juice. Fig. 2 depicts the control volume of the jaggery furnace which shows all the material and energy flows, where steady flow is assumed.

The mass balance is a pre-requisite to establishing the energy balance. The mass balance helps quantify flows which would have been difficult to measure. Based on Fig. 2 the mass balance in terms of the absolute amounts of masses used per day is as follows,

Mass of juice + Mass of bagasse + Mass of combustion air + Mass of chemicals and okra = Mass of flue gas + Mass of jaggery + Mass of water evaporated + Mass of ash + Mass of floating residue

$$m_{\text{juice}} + m_{\text{bagasse}} + m_{\text{air}} + m_{\text{chemical \& okra}} = m_{\text{flue}} + m_{\text{jaggery}} + m_{\text{steam}} + m_{\text{ash}} + m_{\text{fr}} \quad (1)$$

2.1.1. Energy balance

From the flows in Fig. 2, the energy balance is established as follows,

Energy rate from bagasse = Energy rate for sensible heating of juice + Energy rate for juice evaporation + Energy rate in liquid jaggery + Energy rate carried in flue gas + Energy rate from wall losses + Energy rate lost from ash + Energy rate lost in unburnt fuel

$$\dot{E}_{\text{bagasse}} = \dot{E}_{\text{pre-heat}} + \dot{E}_{\text{evap}} + \dot{E}_{\text{jaggery}} + \dot{E}_{\text{flue}} + \dot{E}_{\text{wall losses}} + \dot{E}_{\text{ash}} + \dot{E}_{\text{unburnt}} \quad (2)$$

From the energy balance, the energy efficiency of the combustion process can be calculated. The efficiency of a process is useful in assessing its performance and is the ratio of the useful output to the supplied input. It is calculated as,

$$\eta_{\text{energy}} = \frac{\dot{E}_{\text{jaggery}} + \dot{E}_{\text{evap}} + \dot{E}_{\text{pre-heat}}}{\dot{E}_{\text{bagasse}}} \quad (3)$$

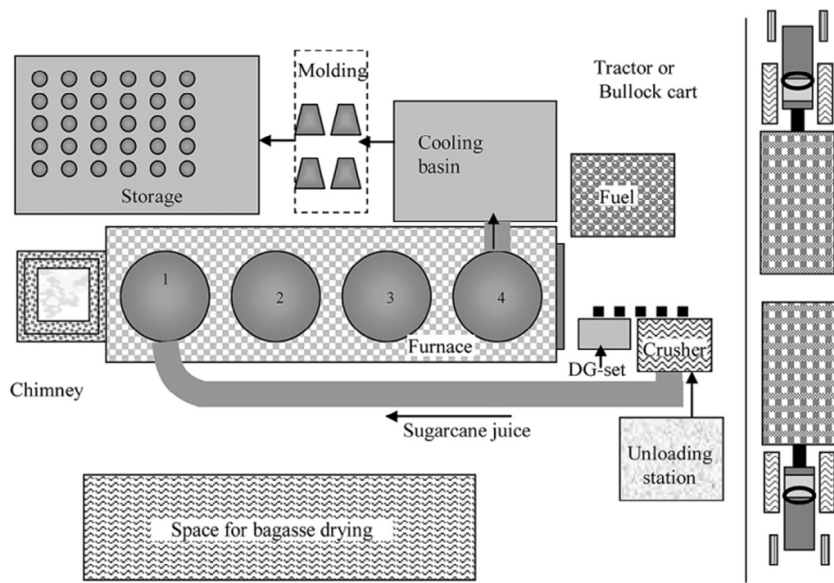


Fig. 1. Jaggery processing setup (Sardeshpande et al., 2010).

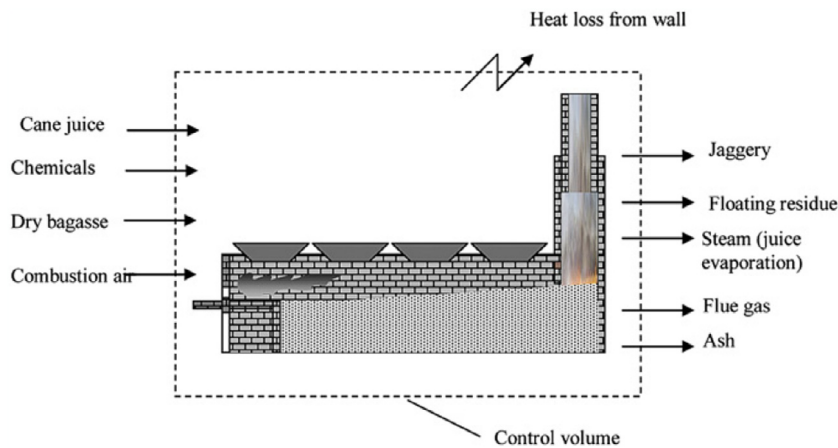


Fig. 2. Jaggery furnace control volume.
Source: Adapted from Sardeshpande et al. (2010)

Table 1
List of instruments used for measurements (Cordeiro et al., 2004).

Instrument	Specification
Weighing balance	Range: 0.25–20 kg Least count: 50 g
Stop watch	Least count: 1 s
High temperature sensor	Range: 0–1200C
K-type thermocouple	Least count: 1C
RTD for ambient temperature measurement	Range: 0–200C Least count: 0.1C
Dry flue gas analyser for oxygen (O2) and carbon monoxide (CO) sensing	Range: 0%–21% O2 and 0–20,000 ppm CO Least count: 0.1 O2 and 1 ppm CO

where the energy used for preheating is the sensible heating of the cane juice up to the boiling point. \dot{E}_{evap} is the energy rate used during evaporation and $\dot{E}_{jaggery}$ is the heat rate carried away by the finished product. Even though all of the latent heat of evaporation and part of the preheat energy is lost from the system, it directly contributes towards the useful product (condensed juice) and is therefore considered a useful output energy flow. The mass and energy balances are described in further detail in Sardeshpande et al. (2010).

2.1.2. Exergy balance

While energy efficiency is a measure of performance, it does not give any indication of the degradation of resource quality, whereas exergy analysis can overcome this shortcoming. Unlike energy, exergy is not a conserved quantity. When setting up an exergy balance there is a portion that is destroyed, which is caused by the irreversible nature of real thermodynamic processes. The loss of exergy, as resources flow through a system can be considered an indicator of resource consumption and is a variable of interest in

this analysis. The general exergy balance for a steady state system is as follows,

$$\dot{E}x_{in} = \dot{E}x_{out} + \dot{E}x_{dest} \quad (4)$$

The exergy balance for the mass and energy flows in Fig. 2 is given as,

$$\begin{aligned} \dot{E}x_{juice} + \dot{E}x_{bagasse} + \dot{E}x_{air} + \dot{E}x_{chemicals} \\ = \dot{E}x_{jaggery} + \dot{E}x_{flue} + \dot{E}x_{wall-losses} + \dot{E}x_{ash} \\ + \dot{E}x_{vapour} + \dot{E}x_{fr} + \dot{E}x_{dest} \end{aligned} \quad (5)$$

The mass of chemicals and okra juice are 0.04% each per kilogramme of product. The chemicals are calcium carbonate and phosphoric acid with specific chemical exergies of approximately 18 kJ/mol 107 kJ/mol respectively. Okra juice is mainly composed of protein, fat, sugar and moisture (Adelakun et al., 2009), and since it is used in minute quantities, the chemical exergies of okra juice can be safely neglected. Similarly, on the output side, the floating residue is 1.5% by mass of the cane-juice at the point at which it is skimmed off. The floating residue being composed of sand and bagasse fibres, its small quantity and chemical composition allows one to safely neglect the exergy associated with this stream. Finally, the air used in the combustion process is fresh air from the reference environment, which has zero exergy by convention. The simplified balance is then as follows,

$$\dot{E}x_{juice} + \dot{E}x_{bagasse} = \dot{E}x_{jaggery} + \dot{E}x_{flue} + \dot{E}x_{wall losses} + \dot{E}x_{ash} + \dot{E}x_{vapour} + \dot{E}x_{dest} \quad (6)$$

The performance indicator, exergy efficiency is defined as,

$$\eta_{exergy} = \frac{\dot{E}x_{jaggery} + \dot{E}x_{vapour}}{\dot{E}x_{bagasse}} \quad (7)$$

where $\dot{E}x_{jaggery}$ is the exergy rate of the produced jaggery, $\dot{E}x_{vapour}$ is the exergy rate carried away by the water vapour leaving the system and $\dot{E}x_{bagasse}$ is the supplied exergy rate of bagasse for combustion. The exergy balance is composed of a variety of mass and energy flows. The calculation of each term is described now.

A classification of different types of exergy has been given by Gundersen (2009), broadly categorized into physical and chemical exergy. Further detail about exergy and its application to manufacturing processes can be found in Avenue and Walford (1996), Bejan (1988), Dincer and Rosen (2012), Khattak et al. (2012) and Tsatsaronis et al. (2007). The calculation methods for each term in the exergy balance corresponding to their respective exergy flows will now be explained.

2.1.3. Specific exergy of sugar cane juice

After crushing the sugar cane, the juice is separated out that is the raw material for the process. For the cane juice flowing at ambient conditions, the physical exergy is negligible while the chemical exergy needs to be calculated. Approximately 85% of the solute is sucrose while there are numerous other carbohydrates, salts and minerals present in minute quantities (Avenue and Walford, 1996). However, for simplicity, it is assumed that the cane juice is a solution of only sucrose in water. Additionally, it is assumed that the water is at the condition of the water present in the reference environment, therefore it has negligible exergy. This simplification is reasonable since the specific exergy of water calculated by rather complex methods (Chen et al., 2009), is negligible compared to that of sucrose (Tai et al., 1986). The chemical composition of sucrose is $C_{12}H_{22}O_{11}$ with a specific chemical exergy of 5969.28 kJ/mol or 17.45 MJ/kg (Tai et al., 1986). The cane juice in this case study was measured to have a specific gravity of 18 degrees Brix, meaning that 100 g of solution contained 18 g of sucrose so that the composition of the cane juice was 18% sucrose. The specific exergy of the sugar cane juice flow is therefore 3141 kJ/kg.

2.1.4. Specific exergy of bagasse

The chemical exergy (ϵ_0) of the dry bagasse is calculated through the method proposed by Kamate and Gangavati (2009)

$$\epsilon_0 = [(NCV)_0 + w h_{fg}] \phi_{dry}, \quad (8)$$

where, NCV is the net calorific value, ϕ_{dry} and w are the ratio of the chemical exergy to the net calorific value of the fuel and fraction of moisture in bagasse respectively. The value of ϕ_{dry} depends on the composition of carbon, oxygen and hydrogen in the bagasse and is calculated as,

$$\phi_{dry} = \frac{1.0438 + 0.1882 \left(\frac{h}{c}\right) - 0.2509 \left[1 + 0.7256 \left(\frac{h}{c}\right)\right] + 0.0383 \left(\frac{n}{c}\right)}{1 - 0.3035 \left(\frac{o}{c}\right)}, \quad (9)$$

where c , h , o and n are the mass fractions of carbon, hydrogen, oxygen and nitrogen determined from the ultimate analysis, along with the bagasse moisture content (8%–10%). Therefore, the specific chemical exergy of the bagasse for 9% moisture content is calculated to be 13.2 MJ/kg. It should be noted here that bagasse is considered a renewable exergy source (Contreras et al., 2009; Moya et al., 2013).

2.1.5. Specific exergy of the jaggery produced

The jaggery produced is measured to have a specific gravity of 85 degrees Brix. Therefore, the makeup of jaggery is 85% sugars and 15% moisture. The composition of the sugars in jaggery has been quantified in previously studies (Rao et al., 2007; Singh et al., 2013). Upon heating the cane juice, a part of the sucrose is converted to glucose and fructose. Both of these sugars have the same chemical formula ($C_6H_{12}O_6$) and therefore have the same specific chemical exergy of 2975.85 kJ/mol or 16.5 MJ/kg (Tai et al., 1986). In view of the values of mass flow rate and temperature at which the jaggery is produced, the thermo-mechanical, kinetic and potential exergy can be safely neglected. The total specific exergy of the jaggery is therefore 14 025 kJ/kg.

2.1.6. Specific exergy of the water vapour

The exergy of the water vapour that leaves the system as a result of heating the cane juice is calculated as,

$$\dot{E}x_{vapour} = \dot{m}_{vapour} [(h - h_0) - T_0 (s - s_0)] \quad (10)$$

The enthalpy and entropy values are taken from steam tables; the specific exergy of the vapour leaving the system is calculated to be 488.4 kJ/kg.

2.1.7. Exergy of the flue gas

At atmospheric pressure, and temperature above 700 °C, flue gas can be safely assumed to be an ideal gas with its constituents being the combustion products, CO_2 , H_2O and N_2 . The exergy of this flow is comprised of the thermo-mechanical and chemical parts. N_2 , H_2O (l), and CO_2 have standard chemical exergies of 0.77 kJ/mol, 0.72 kJ/mol and 19.6 kJ/mol respectively. H_2O in gas state has a higher standard chemical exergy but that is linked to its enthalpy of vaporization which has already been taken into account within the exergy of water vapour. Therefore, the only significant chemical exergy contribution is due to CO_2 , and that of H_2O and N_2 can be safely neglected. The total exergy of the flue gas is calculated as follows,

$$\dot{E}x_{flue} = \dot{m}_{flue gas} \left[C_p (T_{flue} - T_0) - C_p T_0 \left(\ln \frac{T_{flue}}{T_0} \right) \right] + Ex_{ch, CO_2} \quad (11)$$

The chemical exergy is kept separate from the thermo-mechanical part, to suit further study related to integration with secondary processes, since thermo-mechanical and chemical exergies are very different in their nature.

Table 2
Chemical composition of residual sugarcane bagasse ash [Cordeiro et al. \(2004\)](#).

Component	Weight fraction (%)	Component	Weight fraction (%)
SiO ₂	78.34	MnO	0.13
Al ₂ O ₃	8.55	TiO ₂	0.50
Fe ₂ O ₃	3.61	MgO	1.65
CaO	2.15	BaO	<0.16
Na ₂ O	0.12	P ₂ O ₅	1.07
K ₂ O	3.46		

2.1.8. Specific exergy of bagasse ash

Bagasse ash composition, dominated by SiO₂ was analysed by [Cordeiro et al. \(2004\)](#) and is shown in [Table 2](#). Considering the top five compounds that the form 96.1% of the bagasse ash by mass; the chemical exergy is calculated to be 244.2 kJ/kg as detailed in [Table 3](#). Considering the heat lost by bagasse is 0.37% of the flue gas, its thermal can be neglected. The specific exergy of the bagasse ash is therefore equal to its specific chemical exergy (244.2 kJ/kg).

2.1.9. Exergy of furnace losses

A portion of the heat supplied is also lost from the furnace through the walls and ground. The surface temperature of the physical boundary of the furnace varies as it depends on the inside surface temperature which is variables across the length and width of the furnace. The control volume for analysis is taken outside the furnace wall such that the low grade heat lost from the walls, and through the ground is at the environmental temperature, resulting in a zero exergy flow (Eq. (12)). This lost exergy can be classified as part of the total exergy destruction in the system, which is seen in the results tables to follow. In view of the magnitudes of this flow in the energy balance and the grade of thermal energy of these losses, the selection of system boundary is a reasonable simplification.

$$\dot{E}x_{wall\ losses} = \dot{Q}_{losses} \left(1 - \frac{T_0}{T}\right), \quad (12)$$

where T is the temperature of the heat stream and in this case, is the same as T_0 . By modelling all the mass and energy flows in terms of exergy, the exergy balance was implemented and the results are shown in [Tables 4](#) and [5](#) in the following section.

3. Results and discussion

[Table 4](#) provides the results obtained from the exergy balance in which all mass and energy flows are represented in common units in terms of exergy. The performance comparison results in [Table 5](#) show that the energy and exergy efficiencies increase by 11% and 10.3% respectively. The exergy destruction rate reduced by 119 kJ/s, or 0.9% from the baseline scenario. Three of the four indicators suggest an improved system whereas the percentage of exergy destroyed almost remains the same. Considering exergy destruction is more than one third of the supplied exergy in both the operational conditions, it merits further investigation. Additionally, it should be noted that the flue gas temperature was previously measured at the chimney which ranged from 950 °C to 1050 °C for the baseline and 650 °C to 750 °C for the modified scenario ([Sardeshpande et al., 2010](#)). On average, the flue gas temperature

was measured to be approximately 1000 °C and 700 °C for the baseline and modified scenario, for which the corresponding values of C_p have been used. Furthermore, the uncertainty associated with the results obtained is also provided in the tables ([Taylor, 1997](#)).

3.1. Exergy destruction in the process

There are two dominant exergy supplies to the system therefore two sources of exergy consumption, namely the juice and bagasse. As the juice is heated up, the sucrose (C₁₂H₂₂O₁₁) molecules are broken down into glucose/fructose (C₆H₁₂O₆). Sucrose being the more complex molecule has a greater specific chemical exergy, 3141 kJ/kg as compared to glucose/fructose (14025 kJ/kg). For the mass flow rates of the cane juice and jaggery of 0.108 kg/s and 0.02 kg/s respectively, there is an unavoidable exergy destruction rate of 58.7 kJ/s. This exergy loss is related to the changes in the chemical structure of the sugars that flow through the process. If exergy is considered to be a measure of resource value ([Rosen, 2008, 2002; Valero et al., 2010](#)), then the breaking down of sucrose molecules to glucose and fructose represents a theoretical loss of value. Since, this loss is exactly the same in both scenarios, it is clearly not affected by the process modifications. Bagasse being the second major source of exergy, it is analysed next.

The furnace operation was analysed in detail to understand how well the combustion process utilized the renewable resource (bagasse) supplied. [Table 6](#) shows the results of an exergy balance when the combustion is taken into account while ignoring the chemical exergy aspect. This allows one to understand how efficiently the bagasse is used by the furnace for combustion. The results from [Table 7](#) show that the process modifications increased the energy and exergy efficiencies by 11% and 3.7% respectively. The rate of exergy destruction decreased from 424.5 kJ/s to 314.5 kJ/s, however as a proportion of the exergy input to the furnace, it actually increases by 7.4%. While the increase in efficiency and decrease in the absolute value of exergy destruction are beneficial for resource efficiency, the increased proportion of exergy destruction is a negative impact and is discussed in detail in the following section.

3.2. Implications of the results

The results in [Table 7](#) show that both in the baseline and modified scenario, exergy destruction is the biggest source of exergy loss, an indicator of unrecoverable resource consumption. In baseline operation, exergy destruction rate was 65.2% (516.8 kW) of the bagasse exergy supply rate while the flue gas was less than half at 29.1% (230.7 kW). This difference further increased in the modified operation where exergy destruction became 72.6% (357.3 kW) of the bagasse exergy supplied as compared to flue gas which stood at 18.5% (90.2 kW). Summarizing, a greater proportion of the supplied resource is lost in terms of unrecoverable exergy destruction, even though the process utilizes a smaller absolute quantity of the fuel. These are additional pieces of information in comparison with an energy analysis which can aid decision making towards process improvement.

Table 3
Chemical exergy of bagasse ash.

Compound	Specific Ch. exergy (kJ/mol)	Specific Ch. exergy (kJ/kg)	Mass fraction (%)	Ch. exergy per kg of bagasse (kJ/kg)
SiO ₂	2.2	36.18	78.34	28.34
Al ₂ O ₃	15	147.11	8.55	12.57
Fe ₂ O ₃	12.4	77.64	3.61	2.80
CaO	127.3	2269.97	2.15	48.78
K ₂ O	413.1	4385.35	3.46	151.73
Total			96.11	244.22 kJ/kg

Table 4

Exergy balance results for the jaggery making process.

Flows IN	Baseline operation				Modified operation			
	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Uncertainty (\pm kJ/s)	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Uncertainty (\pm kJ/s)
Juice	0.11	3141.00	339.23	6.51	0.11	3141.00	339.20	6.51
Bagasse	0.06	13200.00	792.00	16.95	0.04	13200.00	492.00	10.53
Air ^a	–	0	0	–	–	0	0	–
Flows OUT	Baseline operation				Modified operation			
	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Uncertainty (\pm kJ/s)	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Uncertainty (\pm kJ/s)
Jaggery	0.02	14025.00	280.50	5.53	0.02	14025.00	280.50	5.53
Water vapour	0.09	488.40	43.90	1.05	0.09	488.40	43.90	1.05
Flue gas	0.34	678.7 ^b +445.4 ^c	382.20	38.87	0.25	360.8 +445.4	201.60	20.50
Losses ^d	–	–	0	–	–	–	0	–
Ash	1.5E–03	244.20	0.36	7.2E–04	0.00	244.22	0.02	4.8E–05

^a Air supplied is at environmental temperature which has zero exergy.^b Thermo-mechanical exergy.^c Chemical exergy of carbon dioxide, transiting exergy in this case.^d Thermal wall losses calculated from energy balance and not measured.**Table 5**

Energy and exergy performance comparison.

	Baseline operation	Modified operation	Percentage change
Energy efficiency ^a	29%	40%	11%
Exergy efficiency	28.7%	39%	10.3%
Exergy destruction	424 kJ/s or 37.5%	305 kJ/s or 36.7%	0.9%

^a Energy efficiency results from [Cordeiro et al. \(2004\)](#).**Table 6**Exergy balance table for analysing the combustion performance of bagasse.^a

Flows IN	Baseline operation		Modified operation	
	Value (kJ/s)	Uncertainty (\pm kJ/s)	Value (kJ/s)	Uncertainty (\pm kJ/s)
Bagasse	792 (100%)	2.4	492 (100%)	10.5
Air	0	0	0	0
Flows OUT	Baseline operation		Modified operation	
	Value (kJ/s)	Uncertainty (\pm kJ/s)	Value (kJ/s)	Uncertainty (\pm kJ/s)
Jaggery heat content	0.64 (0.1%)	0.013	0.64 (0.1%)	0.013
Vapour	43.9 (5.4%)	1.05	43.9 (8.9%)	1.1
Flue gas	230.7 (29.1%)	23.5	90.2 (18.3%)	9.17

^a All percentages in [Table 6](#) are in terms of the supplied bagasse.**Table 7**

Combustion performance comparison between the baseline and modified operation.

	Baseline operation	Modified operation	Percentage change
Energy efficiency	29%	40%	11%
Exergy efficiency	5.62%	9.35%	3.73%
Exergy destruction	65.2% or (516.8 kJ/s)	72.6% or (357.3 kJ/s)	7.4%

Grassmann diagrams are an effective way of presenting the exergy flows and consumptions associated with resource transformations in processes. [Fig. 3](#) is a depiction of the jaggery process if it were to be integrated with a secondary process to minimize non-renewable resource use on a larger scale. A hypothetical secondary process (called X), which is fed by non-renewable fuel, is to be integrated with the jaggery process in such a way that its fuel use can be reduced through the input of waste heat from flue gases of the jaggery process and the left over bagasse. In practice, examples of bagasse using systems are ethanol production through a suitable biochemical method or electricity generation in cogeneration systems based on either the Rankine cycle or combined cycle turbines [Dantas et al. \(2013\)](#) and [Hofsetz and Silva \(2012\)](#). The following observations can be made from [Fig. 3](#),

- All varieties of flows in the jaggery process are represented on a common scale which allows an objective analysis of

resource accounting based on the thermodynamic property, exergy.

- The main major unrecoverable exergy loss is that of exergy destruction.
- The wasted flue gas exergy is the second major exergy loss which could be recovered through the use of an appropriate technology.
- Exergy losses from the system due to water evaporation, heat leakage from the furnace and waste ash are minor losses.
- Ash exergy is negligible and can be safely neglected for future exergy analyses.

[Fig. 3](#) essentially depicts how much renewable sourced exergy could be available to a secondary process. Provided the flue gas and bagasse exergy could be utilized by the secondary process, the baseline offers a total reduction of 29.1% (230.5 kW) of the total

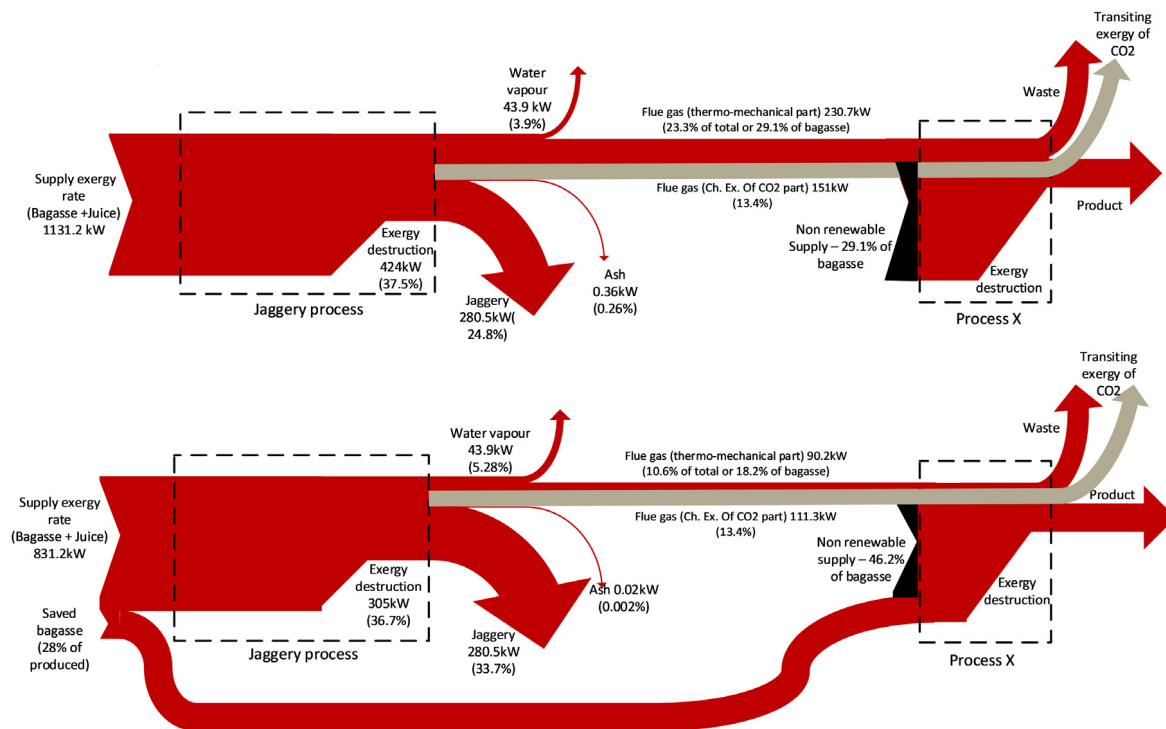


Fig. 3. Integration of the jaggery process with a secondary process X for the baseline operation (above) and modified operation (below). All percentages are in terms of the bagasse supplied to the furnace.

bagasse exergy as compared to 46.2% (365.9 kW) for the modified operation.

4. Summary and concluding comments

This paper presented the first exergy analysis of a jaggery process, and it supplements the current body of literature that is based on energy analysis alone. It provided additional understanding of the resource consumptions in the process in comparison with an energy analysis by taking into account the effect of thermodynamic irreversibilities. Also, modelling all flows on a common unit bases allows comparison of different technology options or configurations to arrive at the most resource efficient solution. Based on the study, the following concluding comments are made,

- Exergy analysis provided an effective means to compare the resource use and understand resource consumption in the two operating scenarios for the jaggery furnace.
- No additional experimental data to that of the energy balance was required for the exergy analysis.
- A significant amount of exergy is wasted through the flue gas if it is not reused. Exergy reuse for displacing the consumption of non-renewables supply in a secondary process is recommended.
- The most significant exergy loss in the furnace is that of exergy destruction due to thermodynamic irreversibilities in combustion.

Exergy being an environment dependent property, future studies could include dynamic analysis using actual temperature data and predictive models. Such a methodology could lead to further improvements in the process in order to extract maximum potential from the renewable fuel, bagasse.

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Author contributions

The main author of the article is Dr. Sanobar Khattak who performed the exergy analysis and wrote the article. Dr. Vishal Sardeshpande performed experimental work and the energy analysis (previous publication) and contributed to idea development. Finally, Dr Richard Greenough and Dr. Neil Brown provided general guidance, idea critique and article internal review.

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